Mon. Not. R. Astron. Soc. **000**, 1–5 (2005) Printed 30 May 2005 (MN LaTeX style file v2.2)

Identification of extragalactic sources of the highest energy EGRET photons by correlation analysis

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ABSTRACT

We found significant correlations between the arrival directions of the highest energy photons ($E_\gamma > 10$ GeV) observed by EGRET and positions of the BL Lac type objects (BL Lacs). The observed correlations imply that not less than three per cent of extragalactic photons at these energies originate from BL Lacs. Some of the correlating BL Lacs have no counterparts in the EGRET source catalog, i.e. do not coincide with strong emitters of gamma-rays at lower energy. The study of correlating BL Lacs suggests that they may form a subset which is statistically different from the total BL Lac catalog; we argue that they are prominent candidates for TeV gamma-ray sources. Our results demonstrate that the analysis of positional correlations is a powerful approach indispensable in cases when low statistics limits or even prohibits the standard case-by-case identification.

Key words: BL Lacertae objects: general - method: statistical - gamma-rays: theory.

1 INTRODUCTION

Identification of point sources observed at different wavelengths is a standard problem in astronomy. This problem becomes very difficult at high energies, when the angular resolution decreases and a mere positional coincidence becomes insufficient for the identification (an example is the EGRET catalog of point sources (Hartman et al. 1999) more than a half of which have no optical/radio counterparts). The photon flux also decreases with energy. Already at EGRET energies the separation of point sources from the diffuse background becomes a challenging problem by itself. At even higher energies, the flux becomes so low that it is more appropriate to think of the data as a collection of individual photons. In this situation, the standard method which consists in finding local excesses of flux and identifying these excesses with astrophysical objects becomes inadequate.

In this paper we argue that in the case of low flux the problem of identification can be approached by an alternative method based on the statistical analysis of correlations between individual photons and a given *catalog* of astrophysical objects. The advantage of this method is that it may give positive identification even in the case when the average number of photons from a source is much less than one. The price to pay is the statistical character of the obtained information: one may establish with certainty that the catalog contains actual sources, but may, in general, not be able to identify them individually, nor estimate the luminosity of a given source. This method has been previously applied to the case of ultra-high energy cosmic rays by Tinyakov & Tkachev (2001, 2002); Gorbunov et al. (2002, 2004); Gorbunov & Troitsky (2004).

Here we apply this method of identification to the catalog of individual photons with energies $E_\gamma > 10$ GeV published recently by Thompson, Bertsch & O'Neal (2004). We demonstrate that the arrival directions of these photons correlate with positions of optically bright BL Lacertae type objects (BL Lacs), that is the BL Lacs are emitters of hard gamma-rays. We then analyse the emission and spectral properties of the correlating objects at different wavelengths and discuss possible implications of this analysis, in particular for the prospects of TeV observations.

2 CATALOGS OF CANDIDATE SOURCES AND GAMMA-RAYS

Blasars, and the BL Lacs in particular, are the active galaxies with jets pointing to the Earth. Many of them are known to be strong gamma-ray emitters (see, e.g., Hartman et al. (1999); von Montigny et al. (1995); Mattox et al. (1997). They are believed to host powerful astrophysical accelerators of very energetic particles.

Current understanding of physical propeties of BL Lacs is far from being complete. The standard approach suggests the two-bump broadband spectral energy distribution (SED;

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see, e.g., Padovani & Giommi (1995); Fossati et al. (1998)). The lower-frequency peak, whose position varies from the infrared (low-energy-peaked BL Lacs, or LBL) to the X-ray (high-energy-peaked, or HBL) band, is often well-measured and is believed to be caused by the synchrotron radiation of relativistic electrons. The second bump is probably due to the synchrotron photons scattering off the same relativistic electrons (self-Compton, SC); its position should be correlated with that of the first bump and varies from MeV (LBL) to TeV (HBL) gamma-rays. Due to a scarcity of the gamma-ray data, the SC bumps are generally studied much worse than the synchrotron ones.

While the two-bump SED is inherent to the electron-powered jets, strong gamma-ray emission from BL Lacs is expected also in other models, e.g. in the 'proton blazar' model (Mannheim 1993) where it inevitably accompanies the acceleration of protons. Not surprisingly, many of blasars have been identified as EGRET sources (Hartman et al. 1999; von Montigny et al. 1995; Mattox et al. 1997). There are no reasons for the gamma-ray spectra of blasars to have a cutoff at the EGRET energies; at least some of the objects are likely emitters of photons at higher frequencies. In a few cases, this has been confirmed by the TeV observations.

The Table of BL Lac's (Table II) in the catalog of quasars and active galactic nuclei (Véron-Cetty & Véron 2003) consists of objects with different spectral properties which are divided into three classes – confirmed ('BL'), high-polarization ('HP'), and probable/possible ('BL?') BL Lacs. This division is made according to several criteria (some of which are discussed by Véron-Cetty & Véron (2000)) and may reflect important differences in physical properties of the objects. In our correlation analysis we test these three subclasses separately. Each of them we divide in addition into optically bright ($V < 18$ mag) and dim ($V \geqslant 18$ mag) parts. In this way we obtain three subsamples of optically bright BL Lac's:

(1) The set of all confirmed 'BL' type objects with the visual magnitude $V < 18$ mag. This set of BL Lac's contains 178 objects.

(2) The set of all confirmed 'HP' type objects with the visual magnitude $V < 18$ mag. This set of BL Lacs contains 47 objects.

(3) The rest of the objects listed in the Table II of the catalog (Véron-Cetty & Véron 2003) with the visual magnitude $V < 18$ mag. This set consisting of bright unconfirmed BL Lac's contains 81 object.

The catalog of EGRET gamma-rays of the highest energies ($E_\gamma > 10$ GeV) contains 1506 events (Thompson, Bertsch & O'Neal 2004). To suppress the background of Galactic gamma-rays we make a cut on the Galactic latitude, $b > 10°$. This reduces the number of events down to 613.

3 PROCEDURE

Our analysis is based on the calculation of the angular correlation function as described by Tinyakov & Tkachev (2001). The statistical significance of correlation is estimated by testing the hypothesis that the highest energy gamma-rays observed by EGRET and candidate sources are *uncorrelated*. This is done as follows. For a given set of sources and the angle δ, we count the number of pairs *source – gamma ray* separated by the angular distance less or equal to δ, thus obtaining the *data count*. We then replace the real data by a randomly generated Monte-Carlo set of gamma-rays and calculate the number of pairs in the same way, thus obtaining the *Monte-Carlo count*. We repeat the latter procedure many times calling *successful* those tries when the Monte-Carlo count equals or exceeds the data count. The number of successful tries divided by the total number of tries gives the probability $P(\delta)$ that the excess in the data count occured by chance. The smaller is this probability, the stronger (more significant) is the correlation. The validity of this straightforward approach does not depend (Tinyakov & Tkachev 2004) on the completeness of the catalog of the candidate sources provided simulated sets of events correctly represent the detector exposure.

The Monte-Carlo events are drawn from the pool of events generated according to the EGRET exposure map (available at `ftp://cossc.gsfc.nasa.gov/compton/data/egret/high_level/combined_data/`). The latter depends on energy; we adopt the map relevant for the highest energy range 4 GeV $\lesssim E_\gamma \lesssim$ 10 GeV. In our case the energy range is even higher; however, the corresponding exposure map is not available. We expect that this does not significantly influence our results.

The significance of correlations is determined by the probability $P(\delta)$ evaluated at the optimum value of δ which can be obtained by Monte-Carlo simulations (Tinyakov & Tkachev 2001; Gorbunov et al. 2004). This optimum value is usually close to the detector angular resolution. The EGRET detector has been carefully calibrated by Thompson et al. (1993); its angular resolution depends on both the energy and the inclination angle. Averaged angular dispersion contains a narrow component and a wide-angle tail and can be fitted at a given energy by four Gaussians. The radius of a circle containing 67% of the gamma-rays depends on energy as follows (Thompson et al. 1993),[1]

$$\delta_{67}(E_\gamma) \leqslant 0.50° \left(\frac{10\ \text{GeV}}{E_\gamma}\right)^{0.534} \qquad (1)$$

which gives an estimate for the angle δ. Because of the complexity of the EGRET angular resolution we do not fix δ by the Monte-Carlo simulation. Instead, we follow an alternative approach which consists in choosing the optimum bin size δ from the data and correcting the corresponding significance by the penalty factor (Tinyakov & Tkachev 2001, 2004; Finley & Westerhoff 2004). We will see in the next section that this approach allows for a simple estimate of significance.

4 RESULTS

4.1 Positional correlations

In Fig.1 we present the probabilities $P(\delta)$ for all three sets of optically bright objects. Sets (1) and (2) exhibit strong

[1] The EGRET detector has been calibrated at energies $E_\gamma \leqslant$ 10 GeV. In what follows we assume that Eq. (1) is valid at least up to $E_\gamma \sim 30$ GeV.

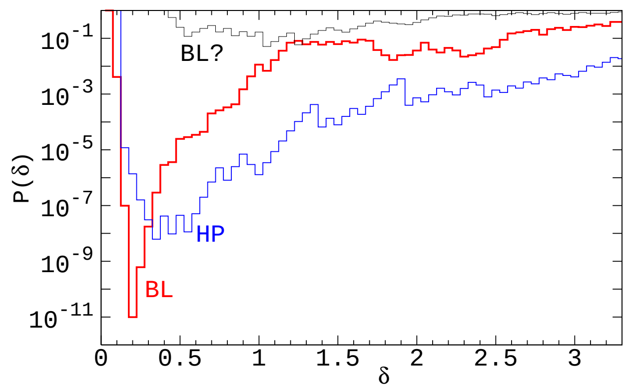

Figure 1. $P(\delta)$ for the sets of bright ($V < 18$mag) 'BL', 'HP' and unconfirmed BL Lacs ('BL?') .

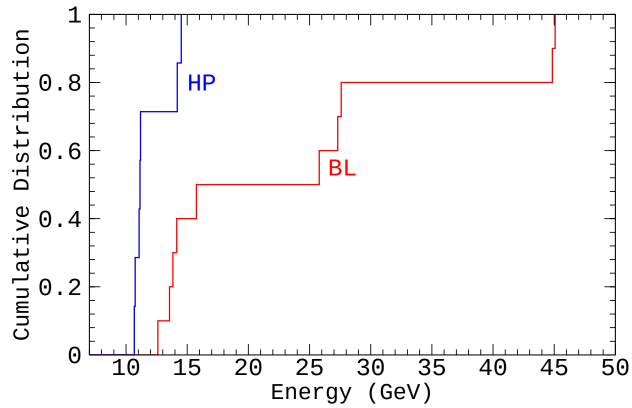

Figure 2. Cumulative distribution of energies of correlating gamma-rays for the sets of 'BL' and 'HP' type objects.

correlations with the EGRET gamma-rays at separation angles compatible with Eq. (1), while correlations with the set of unconfirmed BL Lacs are absent.

For the set (1), the minimum value of $P(\delta)$ is $P \approx 10^{-11}$, and there are 10 events which contribute to correlations in the minimum (0.37 events expected as background from random coincidences). For the set (2), the minimum value is $P = 6.2 \times 10^{-9}$ with 7 events contributing to correlations (0.23 events expected from random coincidences).[2]

To obtain the significance of correlations one may take the lowest value of $P(\delta)$ and multiply it by the penalty factor calculated as described by Tinyakov & Tkachev (2001, 2004); Finley & Westerhoff (2004). This factor is just the number of statistically independent "attempts" to find the lowest probability. In the case at hand it can be replaced by a conservative upper bound: the penalty factor for variation of a quantity cannot exceed the number of steps, that is for δ varying between $0°$ and $3°$ in steps of $0.05°$, the penalty factor is $\leqslant 60$. Multiplying the minimum probabilities in Fig. 1 by 60 clearly would not affect our conclusions.

The minimum of $P(\delta)$ for BLs is at $\delta^{BL}_{\min} = 0.2°$, while the minimum for HPs is at $\delta^{HP}_{\min} = 0.35°$. More compact clustering of gamma-rays around BLs as comapared to HPs can be explained by the difference in the typical energy of correlating gamma-rays (here and in what follows we count the event as correlating if it is at angular separation $\delta \leqslant \delta_{\min}$ for the respective set). As can be seen from Table 1, energies of photons which correlate with BLs are systematically higher as compared to those associated with HPs. It follows from Eq. (1) that the corresonding average angular resolutions are $\langle \delta^{(\mathrm{BL})}_{67} \rangle = 0.34°$, $\langle \delta^{(\mathrm{HP})}_{67} \rangle = 0.46°$, that could explain the observed hierarchy $\delta^{(1)}_{\min} < \delta^{(2)}_{\min}$.

Cumulative distributions of energies of gamma-rays correlating with BL and HP are shown in Fig. 2. The Kolmogorov–Smirnov (KS) test gives P=1.4% for the probability that both sets of photons are drawn from one and the same distribution. The significance is not high, so the systematic difference in energies could have occured by chance. Nevertheless it gives a hint that 'BL' and 'HP' objects may have physically different spectra of gamma-rays. This issue cannot be elaborated further, in particular, because of the lack of knowledge of the distances to the objects in Table 1. Note that PKS 0208-512 has a redshift z=1 implying that the observed photon had two times higher energy at the source.

Optically faint objects, $V > 18$ mag, of all three types (BL, HP and unconfirmed BL Lac's) do not correlate with gamma-rays. For these subsets $P(\delta) \gtrsim 10\%$ in the range of δ compatible with Eq. (1).

name	t	Id	z	V	F_5	E_γ
PKS 2005-489	BL	T	0.071	12.8	1.19	13.8
ON 231	BL	E,G	0.102	16.1	0.72	27.3
TXS 1914-194	BL		0.137	15.3	0.41	27.6
TXS 0506+056	BL	G	?	16.0	1.03	44.9
						45.1
RBS 76	BL		?	16.3	?	25.8
IVS B0621+446	BL		?	16.8	0.37	12.6
RGB J0806+595	BL		?	17.2	0.04	13.6
3EG J0433+2908	BL	E,G	?	17.8	0.48	14.1
						15.7
Mrk 421	HP	E,G,T	0.031	12.9	0.70	14.2
PKS 2155-304	HP	E,T	0.116	13.1	0.41	11.1
						11.1
						11.2
TXS 1215+303	HP		0.237	15.6	0.42	10.7
PKS 0208-512	HP	E,G	1.003	16.9	3.21	10.7
TXS 0912+297	HP		?	16.4	0.20	14.5

Table 1. BL Lac's from the samples (1), (2) ('BL' and 'HP' in column 't') and correlating gamma-ray events. In the column 'Id', 'E' indicates that the object is an EGRET source (Hartman et al. 1999) (positional identification of the corresponding events with the 3EG sources has been claimed by Thompson, Bertsch & O'Neal (2004)), 'G' – that it is a GeV source (Lamb & Macomb 1997) and 'T' – that it is a TeV source. The visual magnitudes are presented in column 'V', the redshifts are presented in column 'z' (the question mark througout the table indicates that the value is unknown); the column 'F_5' presents the radio-flux at 5 GHz in Jy (V, z and F_5 are taken from Véron-Cetty & Véron (2003)). Note that 3EG J0433+2908 and TXS 0506+056 correlate with two gamma-rays each, while PKS 2155-304 correlates with a triplet.

[2] We report the probability calculated from the data count and average Monte-Carlo count assuming the Poisson distribution. This is a sufficiently good approximation at small angular scales. The direct calculation of probabilities below 10^{-5} is not feasible.

4.2 Physical properties of correlating BL Lacs

The important question is which observational and/or intrinsic properties may distinguish efficient high-energy gamma-ray emitters. To systematically study this issue we carry out the KS test for compatibility of the distributions of correlating (without any cut on V) and of all objects of the same type (BL, HP) with respect to various parameters. Unlike correlations discussed in the previous section, this study may be affected by incompleteness of the catalog (Véron-Cetty & Véron 2003), so the results of this section should be interpreted with care.

Some of the correlating BL Lacs are emitters of multiple photons, see Table 1. It is possible to treat such objects in two ways. In the first approach multiple emitters are treated on equal footing with the rest of correlating BL Lacs. In the second approach multiple emitters are given weight which equals the number of photons observed from them. For the sake of completeness we present the results of both approaches.

In Fig. 3 we compare the cumulative distributions of visual magnitudes, radio-fluxes at 5 GHz and X-ray fluxes[3] at 1 keV for correlating and all objects of types 'BL' and 'HP'. Displayed curves correspond to the second approach when multiple emitters are weighted according to the number of observed photons. This allows to see positions of multiple emitters within relevant distributions. The results of the KS test for the first approach are given in parentheses.

In Fig. 4 we compare the cumulitive distributions with respect to spectral indices. The radio-to-optic α_{RO}, radio-to-X-rays α_{RX} and optic-to-X-rays α_{OX} indices are defined as $\alpha_{AB} = \lg(\nu_A F_A/\nu_B F_B)/\lg(\nu_A/\nu_B)$, where F_A is the fluency at a frequency ν_A. These parameters reflect intrinsic properties of the objects and are important for understanding the acceleration mechanism operating inside the sources. In particular, α_{OX} effectively measures the position of the synchrotron bump in the blazar's SED.

Important physical information is contained also in the gamma-ray SEDs of the objects, which are available for the EGRET sources only (two objects of the BL type and three HPs). The EGRET spectral indices of these five objects are unusually small, indicating higher fluency at higher energies. This is fully consistent with identification of them as the sources of $E_\gamma > 10$ GeV photons.

The sources of the 'HP' class have spectral indices $\alpha_{OX} \gtrsim 0$ indicating that most of them are the HBLs with the synchrotron bump in X-rays. The IC bump is then expected at TeV energies, in consistency both with the EGRET spectral indices (for the 3EG sources) and with our evidence for energetic photons for the rest of the sample. Two of the sources have indeed been already detected in TeV.

Much more interesting trends can be seen in the 'BL' sample. Most of these objects have significantly negative α_{OX} and are of the LBL type, which may be also seen directly from the strong dominance of the optical and ra-

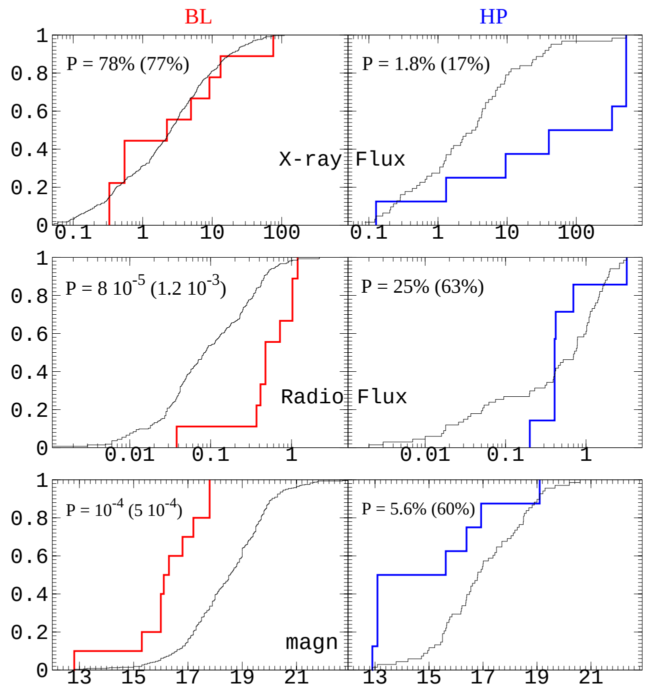

Figure 3. Cumulative distributions of observational characteristics for correlating (thick lines) and all (thin lines) objects of the types 'BL' (left panels) and 'HP' (right panels). Upper panels show distributions of X-ray fluxes ($10^{-12}\mathrm{mW/m^2}$), middle panels correspond to radio flux (Jy) and bottom panels show apparent optical V-magnitudes. P corresponds to the Kolmogorov-Smirnov probability to obtain the distribution of correlating objects as a statistical fluctuation of the distribution of all objects.

dio over X-ray emission (see Fig. 3), suggesting the synchrotron bump in the infrared. This usually corresponds to the sub-GeV IC bump, but the possible detection of $E_\gamma > 10$ GeV photons from them (and, in both available cases, the EGRET spectral indices) indicate rising spectra at GeV energies (cf. the SED of ON 231 in Ghisellini (2004)). Taken at face value, this fact has two immediate consequences: firstly, these objects are good candidates for the detection in TeV (up to now, only one of the eight has been detected); secondly, the two-bump electron-blazar model may not work, in its classical form, for their SEDs. The latter fact could be explained, for instance, by a special geometry of the source (Bednarek 1998) or by a more complicated gamma-ray-emission model. Clearly, the evidence is insufficient to claim that the eight sources considered here represent a new class (e.g., 'proton blazars'). However, one may note that it is the 'BL' objects brighter than 18 mag which correlate with ultra-high-energy cosmic rays[4], and the acceleration of protons should take place in some of them, inevitably accompanied by the emission of energetic gamma-rays. This tempting conjecture awaits further studies with the existing (EGRET) and upcoming (GLAST) gamma-ray data.

Another interesting feature is related to the doublets

[3] The catalog (Véron-Cetty & Véron 2003) contains visual magnitudes and radio-fluxes; X-ray fluxes are taken from the HEASARC database (`http://heasarc.gsfc.nasa.gov`) or calculated based on the count rates given there. Note that the emission and spectra of BL Lacs vary strongly with time, so this study should be considered as indicative only.

[4] This statement relates to the whole sample of 178 objects. Of eight correlating BLs in Tab. 1, only one falls in the errorbox of the arrival directions of cosmic rays – 3EG J0433+2908 coincides with an AGASA-detected doublet.

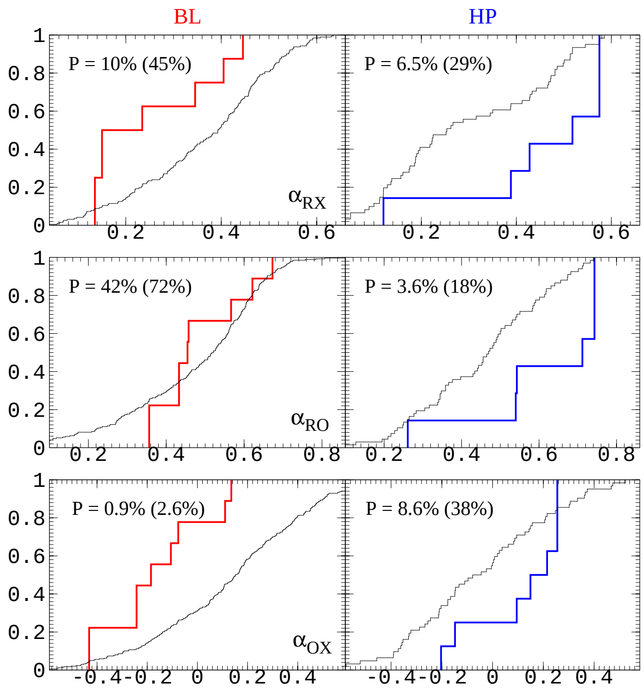

Figure 4. Cumulative distributions of intrinsic spectral properties for correlating (thick lines) and all (thin lines) objects of the types 'BL' (left panels) and 'HP' (right panels). Upper, middle and bottom panels show distributions of α_{RX}, α_{RO} and α_{OX} correspondingly. P corresponds to the Kolmogorov-Smirnov probability to obtain the distribution of correlating objects as a statistical fluctuation of the distribution of all objects.

and the triplet of gamma-rays correlating with BL Lac's. All of them are monochromatic, see Table 1. This may hint at the details of the accelarating mechanism in the sources or ambient matter density and magnetic field strength close to the source.

As we have already pointed out, the small number of correlating photons and incompleteness of the original catalog (Véron-Cetty & Véron 2003) prevent one from making definite conclusions on the basis of the analysis performed in this subsection. However, our results suggest that the BL Lacs which are bright in radio and optical band may often emit energetic gamma-rays. Together with the fact that correlating BL's on average emit more energetic photons (in $E_\gamma > 10$ GeV band, see Fig. 2), this may indicate a deviation from the conventional two-bump SED model, possibly related to the acceleration of cosmic rays.

5 CONCLUSIONS

The statistical analysis we performed in this paper reveals that the arrival directions of the high-energy EGRET photons coincide with positions of BL Lacs ('BL' and 'HP' objects) far too often to be explained by chance: out of 10 coincidences observed for BLs only 0.37 (in average) would be expected if the photons and BLs were uncorrelated. Thus, our analysis has established with certainty that the BL catalog contains sources of gamma-rays. Moreover, nearly all correlating photons are due to sources, and therefore all correlating BLs are likely to be actual emitters (the same concerns HP objects). On the other hand, one may check that there is no significant clustering in the set of highest-energy EGRET photons, so the standard methods of identification would be inconclusive.

The fact of correlations is not the only conclusion which statistical methods are able to establish. As has been shown in sect. 4.2, they allow to address a question of which physical property characterizes the actual emitters. This, however, requires the completeness of the catalog of candidate sources, as well as better statistics.

The authors are indebted to M. Sazhin for useful comments and to S. Sibiryakov for his encouraging interest. The work was supported in part by the grant of the President of the Russian Federation NS-2184.2003.2, by the INTAS grant 03-51-5112 (D.G., P.T. and S.T.), by the grants of the Russian Science Support Foundation and of the "Dynasty" foundation (awarded by the Scientific board of ICFPM; D.G. and S.T.), by IISN, Belgian Science Policy (under contract IAP V/27; P.T.). D.G. thanks CERN TH Division, where the scientific part of the work has been accomplished, for hospitality.

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